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GRINDER EVALUATION AND DEVELOPMENT

A Division of Research and Development
Open-File Progress Report (WP-02-69-26)
written by
Thomas G. Sanders, Sanitary Engineer

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
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ABSTRACT

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The capability of the hammermill to prepare a homogeneous representative sample of refuse for further experimental work is summarized. Also, a definitive exploration is made as to the quantity of moisture driven from refuse while being comminuted.

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CHAPTER I

INTRODUCTION

In 1965, Congress authorized the Solid Waste Disposal Act (P.L. 89-272) making available sums of money to develop more effective solid waste management. Proper solid waste management not only includes ultimate disposal such as sanitary landfilling, but also recycling and reuse of the many constituent materials in solid waste.

Some new methods being considered for solid waste processing include high-temperature incineration, cellulose recovery, pyrolysis, hydrolysis, and others. However, before the majority of these and other processes can be efficiently utilized, much research and developmental work will be required, with emphasis on size reduction and subsequent homogenization. Determination of the operating costs for size reduction is one of many needed points of information in solid waste processing.

Thus far, refuse grinding has been done by machines which were developed for a specific type of relatively homogeneous materials, for example: roller mills for the crushing of coal. These processes have been largely unsuitable for the comminution of a heterogeneous material such as municipal refuse. Therefore, developmental work, in not only operating cost determination and its potential reduction, for available

grinders but also into new comminutor design, will widen the appeal of solid waste presizing.

Better and more complete burning causing an appreciable decrease in residue volume increases the desirability of incineration. Size Reduction Processes can assist the incineration process by: 1 increasing the refuse surface area thereby creating many more sites for rapid oxidation and 2 homogenizing the refuse, dispersing the materials which do not burn with the other more combustible materials, thus providing a feed material to a combustion process with a relatively constant Btu value. This permits better incinerator operation and standardize design. Furthermore, efficient comminution is the first step in the majority of the reuse processes including the many recycling schemes. It is also the necessary first step for proposed solid waste transport schemes utilizing sanitary sewers or pressure piping.

The more uniform, smaller particle size will enable better compaction [ground refuse will compact to higher densities than unground refuse(3)(11)] for the less sophisticated, but nevertheless, important processes such as transfer operations, baling, and sanitary landfilling. Preliminary research indicates that comminuted refuse may be unattractive to flies and rodents, as well as relatively odor free, thus allowing final disposal in landfills without daily cover.(11)(3)

Presently, there is a minimal amount of information pertaining to the comminution of refuse. There are projects in operation funded by the Bureau of Solid Waste Management, which could collect some running cost data. However, the projects thus far have primary goals in other aspects of solid waste processing such as composting, incineration, and cellulose recovery. These efforts use size reduction processes as a means to an end rather than research targets.

It is apparent that a better understanding of both operating costs and grinding theory is needed, before a cost-conscious economical approach can be made into the applicability of grinders to precede the old as well as the new refuse processing methods.

CHAPTER II

THEORETICAL AND EMPIRICAL DEVELOPMENT IN GRINDING

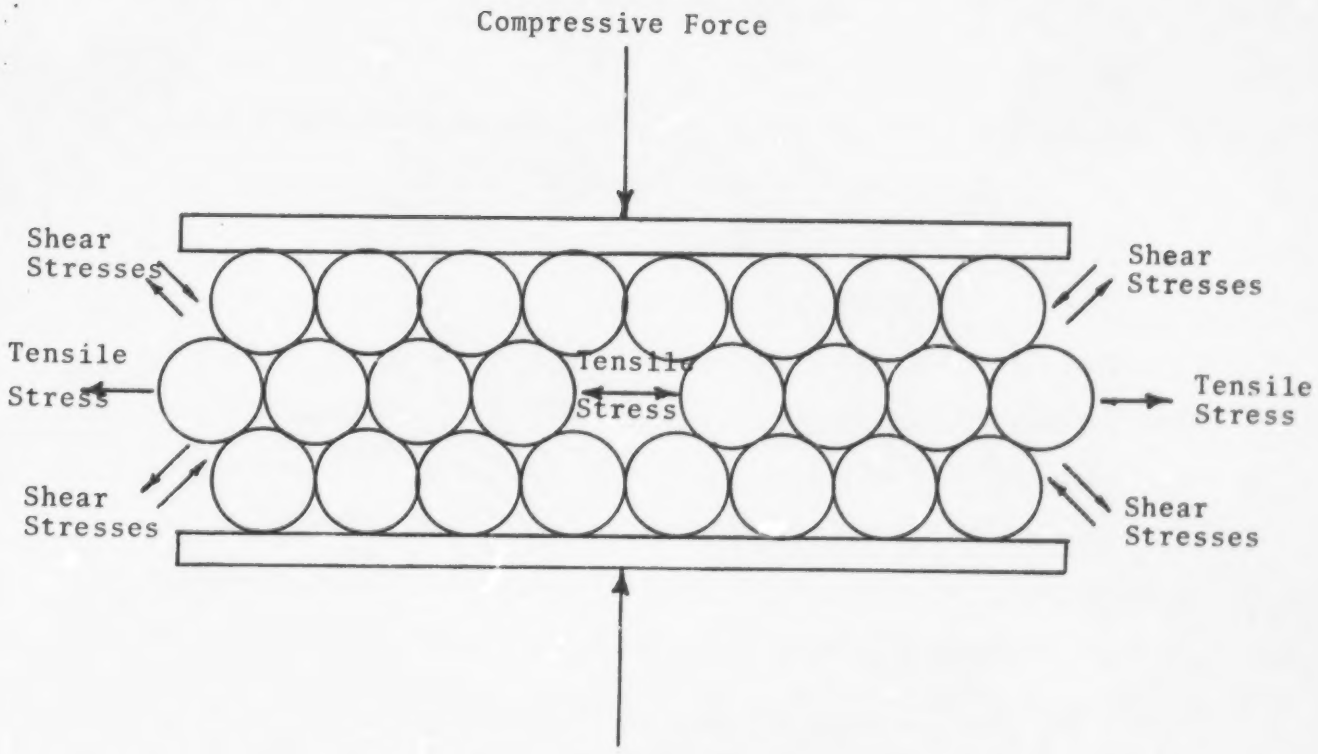
Size reduction is a major unit operation which uses approximately five percent of the world's output of electricity.(2) This is equivalent in amount to all the electricity produced in West Germany or in the United Kingdom. Among the major uses of size reduction processes are the power, cement, and paint industries to name a few. Because of the widespread use of size reducing equipment, much research has been expended to understand and to possibly improve the efficiency of the process. Research has proven that only one to five percent of the total energy input to size reducing processes is used in the actual breakage of particles. The rest of the energy is lost through inefficiency of motor and transmission, friction between particles, friction between particles and machine elements, windage losses, noise, heat, vibration, hysteresis, losses of unfractured material, strain energy among fractured material and energy of transport of material within equipment.(6)

A. Theoretical Development of Communition Theory

Size reduction is a grinding and crushing operation. Crushing denotes size reduction by the application of compression stresses which in turn cause tensile and shear stresses breaking the particle (Figure 1). Grinding, on the other hand,

FIGURE 1: SCHEMATIC DRAWING OF BREAKAGE MECHANICS

Model of crystal lattice to which compressive stress is applied with resultant tensile and shear stresses(2).



is size reduction due to abrasive or attrition forces. Comminution which incorporates grinding and crushing is the general term used to describe refuse size reduction.

The theories which have been derived to describe the comminution processes have evolved from one basic equation.(8)(2)

This equation is:

$$\frac{dE}{dx} = -C\frac{1}{X^N} \qquad \text{(Eq. 1)}$$

Where

E = Energy required per unit weight of material.

X = A factor denoting size.

N = An exponent

C = Constant

The three equations derived from Equation 1 by Rittinger, Kick, and Bond differ as to the definition of particle size, "X," value of the exponent "N" and the value of "C" which describes the resistance of the different materials to comminution. In 1867, Rittinger claimed that "N" was equal to 2 which enabled him to integrate the basic equation (Eq. 1) yielding:

$$E = C_R \left(\frac{1}{X_2} - \frac{1}{X_1}\right) \qquad \text{(Eq. 2)}$$

C_R = Rittinger's Constant

X_1 = Feed Particle Surface Area

X_2 = Product Particle Surface Area

He assumed that the energy consumed in comminution was proportional to new product surface area -X_2-. Kick, fourteen years later, postulated that "N" was equal to 1 which enabled him to integrate Equation 1 giving:

$$E = -C_K \, LOG_e \, (X_2/X_1) \qquad \text{(Eq. 3)}$$

C_K = Kick's Constant

X_1 = Feed Particle Size

X_2 = Product Particle Size

He believed that the energy used in comminution was proportional to the change of particle size of the feed and the final product particle size of an equivalent mass of material. In 1952, Bond believing that both Rittinger and Kick's law did not fully describe comminution, developed from the basic equation a new relationship with the exponent N equal to 1.5 and defining particle size as "an aperture through which 80 percent of the feed or product pass"(2); which allowed him to integrate Eq. 1 yielding:

$$E = 2C_B \left(\frac{1}{\sqrt{X_2}} - \frac{1}{\sqrt{X_1}} \right) \qquad \text{(Eq. 4)}$$

C_B = Bond's Constant

X_1 = Feed Particle Size

X_2 = Product Particle Size

Theoretically, Kick's Law may best be used when the breakage mechanism is purely caused by tensile stresses (when a particle is submitted to pure tensile forces "necking down" and hence new surface area is created which is proportional to work input), and Rittinger's Law may best be used if the breakage mechanism used were purely due to shear stresses

(when a particle is submitted to pure shearing forces work input is not proportional to new surface area but instead, to the number and size of the product particles). Therefore, since comminution is a combination of both shear and tensile stresses, Bond's equation seems to be the most appropriate.

In practice, however, Bond's theory fails to fully describe the theory of comminution. The equation predicts a finite input of energy will be needed to reduce particle size to molecular size which is theoretically impossible since at molecular sizes, the rate of molecule recombination will equal the rate of breaking. Such factors as a build-up of heat, propagation of cracks and the accumulation of strain, all of which would increase the amount of breakage, cannot be described by Bond's formulation even with the more homogeneous type of material. These mechanisms are partially described in the all encompassing empirical determination of the constant factor C_B. Apparently, this value should change with time. The longer the material is comminuted, the larger the change of value C_B.

Theoretically, the amount of energy needed to crush a particular particle would be that energy required to break the bonds of all atoms across a given shearing plane. However, it has been proven that this energy, which is the energy needed to melt the crystal, is never required.(2) Instead,

a small percentage of this total energy is actually needed to break the material. Even the most homogeneous material, such as crystalline sodium chloride has many irregularities or random impurities which concentrate stress and thus allow much less energy than theoretically predicted to crush the material. Therefore, Bond's Law may represent the limit to which theory can be applied in the prediction of any input energy requirements of particle size reduction.

B. Empirical Description of Grinding

Further derivation of formulas to describe comminution especially for refuse will probably have to be limited to empirical formulation since refuse is quite heterogeneous and will continuously vary in particle size, range, and hardness. An empirical approach would have to incorporate the type of refuse (i.e., the percentage of the different constituents), the type of comminuter, and the loss of efficiency due to wear on the different parts of the comminuter.

Empirical determination of the ease of which coal may be ground has been useful in predicting the approximate costs of coal grinding. This grindability index (Ball Mill Index) is determined in the following equation(4):

$$BI = \frac{50,000}{N} \qquad \text{(Eq. 5)}$$

Where

BI = Ball Mill Index

N = number of revolutions required to reduce a weighed sample of coal so that 80 percent of it will pass through a 200 sieve.

The grindability index being a measure of the relative ease to pulverize coal enables the determination of total power needed to pulverize any given type of coal. Obviously with this index, the power required to reduce a coal sample to a predetermined size could be quantified.

Coal grindability can also be determined by using the Hargrove Index which is defined by the empirical relationship(4):

$$HI = 13 + 6.93W \qquad \text{(Eq. 6)}$$

Where

HI = Hargrove Index

W = weight of material passing the No. 200 sieve.

The Ball Mill Index and the Hargrove Index differ predominately as to the type of pulverizer used--a ballmill pulverizer was used for the former and a ball-ring pulverizer for the latter. Widespread use of these empirical indices to measure the grindability of other materials has been limited because of the diversity of pulverizers to be used as well as dissimilarity of the material. Since the grindability of a given material is dependent not only on the material's chemical and physical properties but also on the

type of pulverizer used, grindability indices have been determined on scaled down pulverizers characteristic of the pulverizer to be used. With this index replacing the Ball Mill Index, a better understanding of the power requirements needed for the full scale pulverizer can be obtained.

CHAPTER III

POSSIBLE GRINDING PROCESSES AVAILABLE FOR SOLID WASTES

There are many types of processes available for the comminution of refuse. Each process utilizes either the application of tensile stresses, wearing and grinding forces, or a combination of each to degrade inlet material. A brief description of several of the different processes follows. For a more complete description refer to Reference (4), Chemical Engineer's Handbook.

The hammermill with either fixed or free swinging hammers comminutes the feed material with the application of large tensile forces when the hammers hurl the inlet material against the breaker plate followed by equally strong attrition forces as the material is worn down between the hammers and the outlet grating.

Another process available for the comminution of refuse is the jaw crusher. This device can be visualized as a large vise capable of crushing bulky material by the application of large compressive stresses which in turn cause tremendous tensile stresses and resultant material breakage. Wearing or abrasive mechanics are not utilized in this process allowing very little uniformity of product size. The tumbling rod and ball-mill are processes utilizing wearing and grinding forces to reduce the size of feed material.

Unlike jaw crushers where application of tensile forces is the primary comminution mechanism, the ball-mill relies on the tumbling effect of the ball in a rotating drum to exert attritional forces on the material. A more uniform product size is realized; however, initial maximum size restraint is required.

The disk attritional mill, similar to the ancient buhr-stone mill for grinding wheat to flour, wears down inlet material between disks rotating in the opposite direction. The surface of the disk may be smooth as sandpaper or coarse like a wood rasp, giving a versatility as to the type of material which can be macerated. Rapid wearing out of disk plate surfaces and size restrictions of inlet material lessens the usefulness of this process for the comminution of refuse.

Each of the aforementioned comminutors except for the hammermill have a material specificity with which optimal comminution performance is achieved—jaw crushers, bulky material; tumbling mill, hard brittle material; attrition mills, fiberous and brittle material. The hammermill does not require such material specificity before efficient comminution can take place. The hammermill can effectively macerate a wider range of materials, giving it the versa-tility and durability demanded for the comminution of munic-ipal refuse. Because the hammermill or a slight variation has been the most popular of the many comminutors to

macerate solid waste, it was chosen as the first size reduction process to be studied by the Bureau of Solid Waste Management.

CHAPTER IV

CONTRACTS AND PROJECTS IN BUREAU OF SOLID WASTE MANAGEMENT UTILIZING GRINDERS

SIMILAR PROJECTS

Presently there are no Bureau of Solid Waste Management extramural projects to study the theory and techniques of comminution. However, there are some which utilize size reduction processes.

The following projects, although not in existence to study the comminution of refuse explicitly, will accumulate some data which could be of value in determining the economic cost of refuse comminution.

LIST OF PROJECTS

GRANT NO. AND LOCATION	PROJECT DIRECTOR	TITLE AND OBJECTIVE
D01-UI-00004 Madison, Wisconsin	J. J. Reinhardt	Solid Waste Reduction/ Salvage Plant: Test the Gondard method for processing refuse to reduce volume and produce landfills not attractive to pests.
D01-UI-00030 Gainesville, Florida	W. W. Houston	Gainesville Municipal Compost Plant: Demonstrate newly developed system for medium cities.
D01-UI-00057 Tacoma, Washington	G. M. Schuster	Refuse Crusher - Tacoma, Washington: To demonstrate the feasibility of disposing of demolition wastes by shredding and compacting into a sanitary landfill.

LIST OF PROJECTS (CONTD.)

GRANT NO. AND LOCATION	PROJECT DIRECTOR	TITLE AND OBJECTIVE
DO1-UI-00121	John R. Wolfs	To Determine the Feasibility of Shredding, Mixing, and Composting a Full Range of Municipal Solid Wastes for Reclaiming Submerged Lands: To demonstrate the feasibility of shredding a maximum number of types of municipal solid wastes and to combine these into a dense, compacted, sanitary mass for use as fill in reclaiming submerged lands.
Johnson City, Tenn.	Gordon Stone	Joint PHS-TVA Compost Plant
5-RO1-EC-00259-04 Philadelphia, Pa.	Iraj Zandi	Pipe Transport of Solid Waste
DO1-UI-00091 Buffalo, New York	L. S. Wegman	Bulk Refuse Crusher Facility: To demonstrate the feasibility of presizing bulky municipal refuse prior to disposal by incineration.
DO1-UI-00097 New York, New York	M. Feldman	Shredding of Bulky Wastes for New York City: To develop, design, and construct a facility to shear, shred, or otherwise reduce the widest possible range of bulky solid wastes to manageable size for effective and useful disposal in waterfront land recovery, sanitary landfill, or for preparation for incineration.

LIST OF PROJECTS (CONTD.)

GRANT NO. AND LOCATION	PROJECT DIRECTOR	TITLE AND OBJECTIVE
DO1-UI-00115 St. Louis, Missouri	G. W. Sutterfield	Demonstration of Disposal of Wastes Wood and Bulky Burnable Objects by a Large City: The feasibility of preparing waste wood for sale as pulpwood and the feasibility of effecting size reduction of bulky burnable objects for incineration, at a site not adjacent to the incinerator to develop detailed information concerning the quantities of waste wood and bulky burnable objects generated in a major city.
EC-00333-01 Cambridge, Mass.	D. G. Wilson	Refuse Reclamation by Size Reduction and Separation

CHAPTER V

RESEARCH ACTIVITY: METHODS AND RESULTS

During the initial planning stages of the Waste Handling and Processing Branch, Division of Research and Development grinder and blender evaluation project, several objectives were proposed before the capabilities of the facilities and the required manpower were determined. The objectives included the ability of the grinder and blender to prepare a representative sample, development of a mathematical model correlating power requirement to the type of refuse being ground and a summary of running costs. However, due to the limited capabilities of the facility and manpower, substantial amounts of data which were required for the determination of the mathematical modelwith concomitant running costs could not be obtained. Subsequently, only the evaluation of the hammermill and blender to prepare a representative refuse sample, a brief summary of running costs, and a description of moisture losses while refuse was being comminuted were accomplished.

All research described herein was performed by personnel of the Bureau of Solid Waste Management at the research facility on Center Hill Road. The municipal refuse* used in all

*All unwanted materials which could not be comminuted by the hammermill were separated from the refuse. This material (1 to 2 percent of total weight of sample) included wire, tramp metal, mattresses, large metal containers and furniture.

experiments was obtained from the hoppers of the Cincinnati Center Hill Incinerator.

A. Hammermill and Blender Evaluation to Produce Representative Refuse Sample

Because municipal solid waste is made up of so many different materials which vary in size, shape, density, hardness, degradability, ad infinitum, a problem exists as to what is a representative sample of refuse. Obviously, development of a better technology to handle municipal refuse will have to be preceded by a definitive method to establish a representative sample of solid waste.

It is a fact that solid waste will vary monthly, weekly, daily, etc., so that a representative sample of refuse determined at one point in time may vary immensely from another representative sample determined a short time later. Therefore, it should be made clear that a representative sample of refuse will define only that solid waste from which the sample was prepared. To construe any other data from one representative sample would be foolish. Only when many representative samples are made and analyzed, can any kind of average characteristic be attributed to solid waste from a given location. Expanding this one step further, only after many average representative samples from many locations are summarized, can solid waste characteristic of regions, states, or countries be determined.

A parameter to measure the homogeneity of the refuse to be quantified had to be obtained before a method could be developed to produce a representative solid waste sample. This parameter had to be applicable to all municipal solid waste. Furthermore, the analysis for it should be precise and easy. Therefore after much deliberation, a comparison of moisture contents was decided upon to be the measuring parameter for the relative homogeneity of the refuse sample. If the moisture contents of many refuse samples were approximately the same, then it was thought that any one of these samples was representative of the refuse from which the samples were taken. Other possible parameters to measure homogeneity such as caloric value and organic content were not considered reliable enough due to the imprecise measuring techniques. The oven drying moisture determination was found of adequate precision (Table 1).

Initially the prevailing thought in preparing a representative (homogeneous) sample of refuse was to comminute the refuse in a hammermill* and then mix it in a blender**. To test this hypothesis, seven experiments were run (see Table 1 - Experiment 1 through 7). The experimental procedure entailed the procurement of 1 to 2 tons of municipal refuse, separation of bulky items such as tramp metal, bedsprings, etc., and then grinding in a 1 ton/hr Williams

*The Williams hammermill used has a capacity of 1 ton of refuse per hour. The rotating hammers are free-swinging on a horizontal shaft and powered by a 100 HP electric motor.

**This is a double cone blender with a volume of 70 cubic feet.

hammermill with grates having 1.5 inch diameter perforations with 2 inch centers. The standard deviation of the moisture contents, which is a measure of the fluctuation of samples from a mean, was determined in each experiment and was found to be extremely low. The standard deviation ranged from a low of 0.097 in Experiment 7 to 1.14 in Experiment 3, indicating that a high degree of homogeneity of refuse can be obtained using this method.

Another series of experiments were run to determine if blending was actually necessary to produce a homogeneous sample of refuse. Previous experience indicated that a high degree of mixing did occur using only the hammermill, but the relative amount of homogenation had not been determined.

Additional experiments were run duplicating the sample size and techniques used in Experiments 1 through 7, except that final mixing in the blender was deleted. The results, Experiments 8 through 10 (Table 1), indicate that the standard deviation of the moisture contents is somewhat higher than the standard deviation in the first seven experiments using the blender, but not so high that blending cannot be deleted in the preparation of a representative refuse sample.

Therefore, it appears that grinding and blending, or grinding alone, are both capable of preparing representative samples from large volumes of municipal refuse. However, the increase of precision using the grinder and blender

TABLE 1: MOISTURE CONTENT DATA

A list of the data collected for the establishment of a representative sample of refuse, using moisture dispersion as the determining parameter.

EXPERIMENT NUMBER	MOISTURE CONTENTS	MEAN	STANDARD DEVIATION
1	36.6, 36.3, 34.8	35.9	± 0.93
2	29.1, 30.6, 30.0	29.9	± 0.57
3	22.7, 25.0, 24.9, 24.4	24.3	± 1.13
4	27.3, 26.6, 28.2, 27.9	27.5	± 0.5
5	22.5, 20.7, 20.8, 20.1	21.0	± 1.1
6	13.9, 14.9, 15.7, 14.3, 15.6	14.9	± 0.34
7	16.90, 16.80, 16.50, 16.50, 16.10	16.56	± 0.097
8	16.8, 20.0, 18.9, 20.6, 18.0, 20.4	19.1	± 1.5
9	48.8, 49.3, 50.7, 50.8, 52.0, 52.8	50.7	± 1.5
10	17.6, 69.4, 69.0, 70.4, 69.7, 66.3 68.2, 67.0	68.4	± 1.4

method is not significant enough to offset the time consuming blender operation.

B. Evaluation of Moisture Loss of Ground Refuse

A study to determine the amount of moisture loss from domestic refuse while being comminuted in a hammermill was initiated after the experiments evaluating the grinder and blender as a method to prepare a representative sample of municipal refuse. The proposed experimental procedure was quite simple. The moisture contents of the refuse would be measured before and after comminution with the difference being the moisture loss.

The moisture loss may easily be attributed to the large amounts of heat generated by a process of this type. The heat energy is dissipated in the formation of steam. Some of the steam is condensed on the incoming refuse and the sides of the mill while the rest is vented into the environment. This resulted in a net decrease of the refuse moisture content.

Because of the heterogeneous nature of domestic refuse, managable representative samples for the determination of the moisture content could not be obtained without some gross presizing and homogenizing of the refuse. The gross presizing was done by removing the 1.5-inch grates from the hammermill, therefore eliminating all comminution capabilities of the mill except for the initial crushing taking

place at the breaker plate.

After the refuse was presized to an average diameter of approximately 5 inches, grab samples were selected for the initial moisture content determinations. Afterwards, the 1.5-inch opening grates were placed back into the hammermill. The refuse was comminuted again yielding a final product particle size of less than 1.5-inch cross section diameter. Grab samples were then selected for final moisture content determinations.

The grab samples of refuse used to determine both the initial and final moisture contents in Experiment 11, Table 2, collected from predetermined areas in the refuse pile underneath the hammermill. Taking the initial and final moisture content samples from the same points was done to add more precision to the data by allowing the determination of not only the average moisture loss of the refuse, but also separate moisture losses of the refuse at each of the six predetermined points. In Experiments 12 and 13, Table 2, this was not done, because moisture was added to the presized refuse necessitating a thorough mixing of the the moisture and refuse before the samples could be taken.

The moisture was added to the refuse before the initial moisture content determinations were made to study the effect of increased moisture content on the amount of moisture lost during comminution.

TABLE 2: MOISTURE LOSSES FROM PROCESSED REFUSE

Data accumulated to determine moisture losses as refuse is being comminuted.

EXPERIMENT 11

Area* Sampled	Initial % Moisture Content (After Pregrinding)	Final % Moisture Content (After Final Grind)	% Moisture Lost at Each Point
A	20.7	16.8	3.9
B	23.7	20.0	3.7
C	22.3	18.9	3.4
D	23.9	20.6	3.3
E	26.5	18.0	8.5
F	21.7	20.4	1.3
Mean	23.1	19.1	
Standard Deviation	2.0	1.5	

EXPERIMENT 12

Sample No.**	Initial % Moisture Content	Final % Moisture Content
1	47.6	48.8
2	41.5	49.3
3	46.4	50.7
4	54.0	50.8
5	43.9	52.0
6	51.4	52.8
7	42.0	
8	57.1	
9	58.8	
10	49.7	
Mean	49.2	50.7
Standard Deviation	6.1	1.5

*Area sampled designates specific areas underneath the hammermill which were sampled twice--after pregrinding and then after final grinding.

**Sample number is only for identification and is not related to an area sampled.

TABLE 2(CONTD.): MOISTURE LOSSES FROM PROCESSED REFUSE

Data accumulated to determine moisture losses as refuse is being comminuted.

EXPERIMENT 13

Sample No.	Initial % Moisture Content	Final % Moisture Content
1	50.0	70.4
2	52.7	69.7
3	74.8	66.3
4	69.8	68.2
5	79.6	67.0
6	61.9	67.6
7	58.2	69.4
8	66.6	69.0
Mean	64.2	68.4
Standard Deviation	10.4	1.4

The grab samples in all experiments ranging from 300 to 500 grams were placed in aluminum tares and covered with aluminum foil. The samples were weighed, heated in a drying oven at 100°C for 24 hours, and weighed again. The moisture content was then defined as the weight loss during 24-hour drying divided by the initial weight of the material before drying.

The inability to obtain a precise moisture content especially for the initial moisture determination lessens the significance of the data but does not prevent a reasonable interpretation. Apparently, as water was added to the refuse to raise the moisture content, the precision of the moisture determination was markedly reduced even though mixing and pregrinding of the wetted refuse preceded the determinations. A comparison of the standard deviation of 2.0 for the initial moisture contents of Experiment 11 (no water was added) to Experiments 12 and 13 with standard deviations of 6.1 and 10.4, respectively, shows the lack of precision when water was added.

Unfortunately the pregrinding and mixing was not adequate for uniform distribution of moisture throughout the refuse. However, once the refuse was macerated with grates in place, in all three experiments the moisture in the refuse was evenly dispersed so that a more precise moisture content determination could be made. The standard deviation for

Experiments 11 and 12 was 1.5 and for Experiment 13, the standard deviation was 1.4.

Interpretation of the data from Experiment 11 leads to the conclusion that there did exist a net decrease in the refuse moisture content of approximately 4 percent. For the wetter refuse in Experiments 12 and 13, such a quantitative statement cannot be made since in both experiments the mean final moisture content was greater than the mean initial moisture content.

Because the refuse should not absorb more water than it losses* while being macerated, negates the quantitative significance of the means alone in Experiments 12 and 13. However, adding the means to their respective standard deviations will give a range which will include 67 percent of the moisture determinations. This may at least show an upper limit for moisture losses. In Experiment 12, 67 percent of the initial moisture contents ranged between 74.6 and 53.8 percent, and the final moisture content ranged between 69.8 and 67.0 percent.

Obviously, very little quantitative information may be drawn from Experiments 12 and 13 except it appears that moisture losses greater than 7 percent (this is the difference between the higher limit initial moisture content and lower limit final moisture content) are highly improbable for

*It has been proven by many researchers that large amounts of energy needed for grinding is dissipated in heat, (6) which can be readily assimilated and dispersed by moisture vented as steam.

refuse with high initial moisture content. It is interesting to note, however, that taking the difference between the upper limit initial moisture content and lower limit final moisture content from the data of Experiment 11 gives 7.5 percent which is approximately equal to the corresponding figures from Experiments 12 and 13.

Several months later, after the original moisture determination experiments were terminated, another format was developed to measure the amount of moisture lost during comminution. Instead of taking the difference of the initial and final moisture contents of the refuse to determine the moisture loss; all the refuse was weighed before and after comminution with the difference being the weight of the moisture loss.

Great care was taken to be sure that all the refuse to be ground was weighed accurately as well as being sure that all the refuse which was ground was also weighed. Even the dust from the refuse was swept up and weighed.

At this time, only one experiment has been made using the new format. Fifty-eight hundred pounds of municipal refuse was comminuted causing a net decrease in weight of 347 pounds. The resulting moisture loss of 5.98 percent compares favorably with the data from the previous experiment, i.e., 11, 12, and 13.

In conclusion, even though more experiments are needed, moisture losses do occur while refuse is being comminuted and apparently in an amount independent of the initial moisture content.

C. Operating Costs Evaluation

During the course of the literature review and initial planning of the experiment, development of comminution operating or running costs and a possible correlation between power input and moisture content was deemed to be an immediate goal of the project. Updating comminution theory and development of new hardware specifically for refuse, although equally important, would hopefully follow in future research projects at a scale much larger than the present pilot plant level of capabilities.

Running cost is defined as the actual cost per ton to comminute refuse. This cost includes amortization, preventive maintenance labor, breakdown labor and material repairs, and power costs. Each of these costs may vary depending on location, time of year, and equipment used. Amortization costs will vary with the interest rates as well as the time required to pay off the loan. Labor costs, both maintenance and repair, will also vary depending upon geographical location. Maintenance and repair can show marked fluctuation in cost depending upon the type of machines and quality of personnel. A hammermill may require extensive

maintenance and downtime for repairs, whereas, a jaw crusher may exhibit very little need for repair and minimal maintenance.

The aforementioned costs, although very important, cannot be quantified in a project of this size*. For example, to determine even a gross estimate of downtime would require several thousand hours of grinding time. A summary of maintenance costs also would require much more grinding time than can be accomplished with a pilot plant setup. The initial phase of this project has been devoted to determining the actual power requirements which can easily be measured and are stochastically independent functions of running time.

The power to the 100 horsepower motor driving the hammermill is measured by a continuous recording rectilinear wattmeter with an accuracy of 1 percent full scale (2.0 kilowatts). With a chart speed of 3 inches per minute, the total work, being a function of the area under the curve; can be measured using a planimeter. Not only can the total work exerted by the electric motor be measured using the chart printout, but also the power drawn at any given time can be ascertained, thereby allowing direct measurement of the power requirements of startup and overloadings.

*Plans have been initiated to increase the size and scope of grinding study to include many operating costs not studied at Cincinnati utilizing the facilities at the Joint BSWM-TVA Composting Project, Johnson City, Tennessee.

Thus far, 11 experimental runs have been made measuring the power required to grind municipal refuse. In each experiment, the samples were weighed by the truck scale at the Center Hill Incinerator after and sometimes before* grinding. The experimental samples ranged from 1,000 pounds to 6,000 pounds, depending on the means of transporting the refuse to the Center Hill research facility. The smaller amounts were delivered by the staff dump truck and the larger amounts were delivered by City of Cincinnati packer trucks. All moisture content determinations were made at the conclusion of each experiment.

The data collected in each of the eleven experiments are summarized in Table 3 and includes grinding time (minutes), net work (kilowatt hour), final average moisture content (percent), weight of ground refuse (pounds), and grate size (inches). Data describing the running costs of the ancillary equipment, such as the conveyor belts, are not included.

Originally the main proposal of this project was to summarize running costs and obtain an average power input needed to comminute 1 ton of refuse. The average power input would be measured in kilowatt-hours per ton which could be easily changed to dollars by knowing the cost of electricity. However, preliminary experiments give indication

*The refuse was weighed before and after grinding when it was delivered by the municipal packer trucks. When the trash was delivered by the Center Hill truck, the refuse was weighed only after grinding because of stoppages and breakdowns in the early experiments very seldom was a whole load of refuse ground at one time.

TABLE 3: OPERATING COST DATA

A summary of the data relating power requirements to final moisture content.

Run Number	Grinding Time (min.)	Moisture Content (%)	Net Work (kw hr/ton)	Cost* (cents/ton)	Weight of Ground Refuse (ton)	Grate Size (in.)
1	33.50	15.5	12.8	19.1	0.70	1.5
2	40.25	18.2	15.4	23.1	0.86	1.5
3	35.00	22.2	14.9	22.3	0.50	1.5
4	48.50	13.6	12.5	18.8	0.75	1.5
5	32.00	39.3	20.7	31.1	0.16	1.5
6	26.50	22.9	16.3	24.4	0.58	1.5
7	136.25	21.7	15.9	23.8	2.90	1.5
8	78.50	43.3	12.1	18.1	3.08	1.5
9	98.00	29.3	23.3	35.0	1.80	1.5
10	68.00	43.9	13.3	20.0	2.62	1.5
11	57.00	22.9	21.2	31.8	1.26	1.5

*Assumed cost of electricity is 1.5 cents per kilowatt-hour.

that the power requirements are a dependent function of moisture content thereby negating the value of an average power input of grinding refuse with varying moisture contents.

Hammer wear is another cost item which will be reported in future reports, but as of this writing not enough running time has elapsed to develop hammer weight loss for inclusion into this report.

D. Possible Relationship between Moisture Content and Network

Thus far, the data has indicated (Figure 2 and Figure 3) that the correlation of the moisture content to the net work is not a straight line relationship, but instead a curvilinear relationship. At final moisture content below 33.8 (Figure 2) and 30.2 (Figure 3) percent, the net work approximates a straight line function of moisture content. However, with moisture contents greater than approximately 30 percent, the data points curve back toward and will probably approach asymptotically a line parallel to the absissa axis. The deviation from the straight line relationship (moisture content >30 percent) was certainly expected since refuse with very high moisture contents (70 to 90 percent moisture) would demand less work to comminute, as the majority of the weight would be water requiring no size reduction to pass through the grates. It is also expected that refuse with very low moisture content (<10 percent) that net work will increase

FIGURE 2. HAMMER-MILL WORK VS. PERCENT MOISTURE

THIRD DEGREE POLYNOMIAL:

$Y = -0.00292\,x^3 + 0.20783\,x^2 - 4.04849\,x + 36.63050$

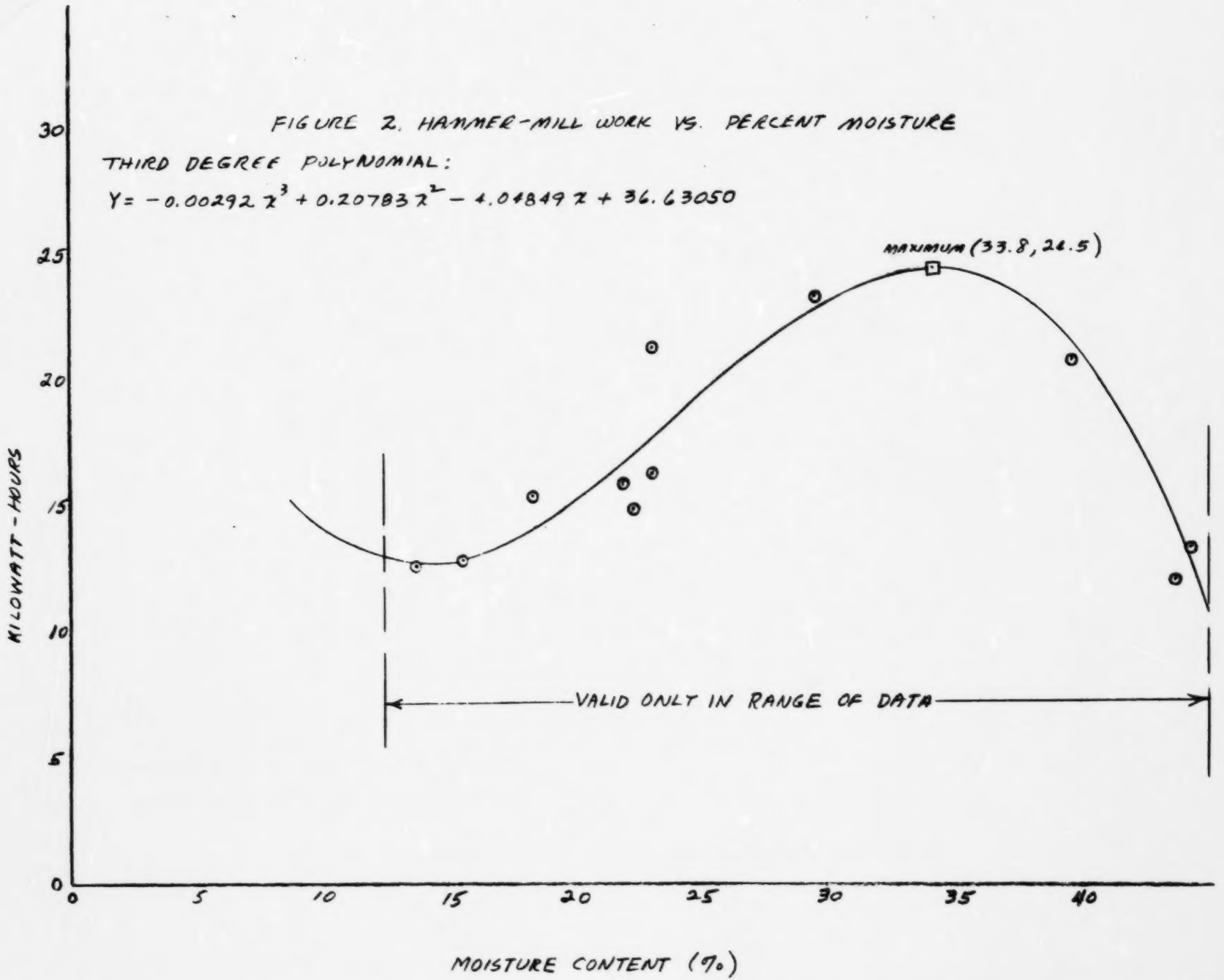
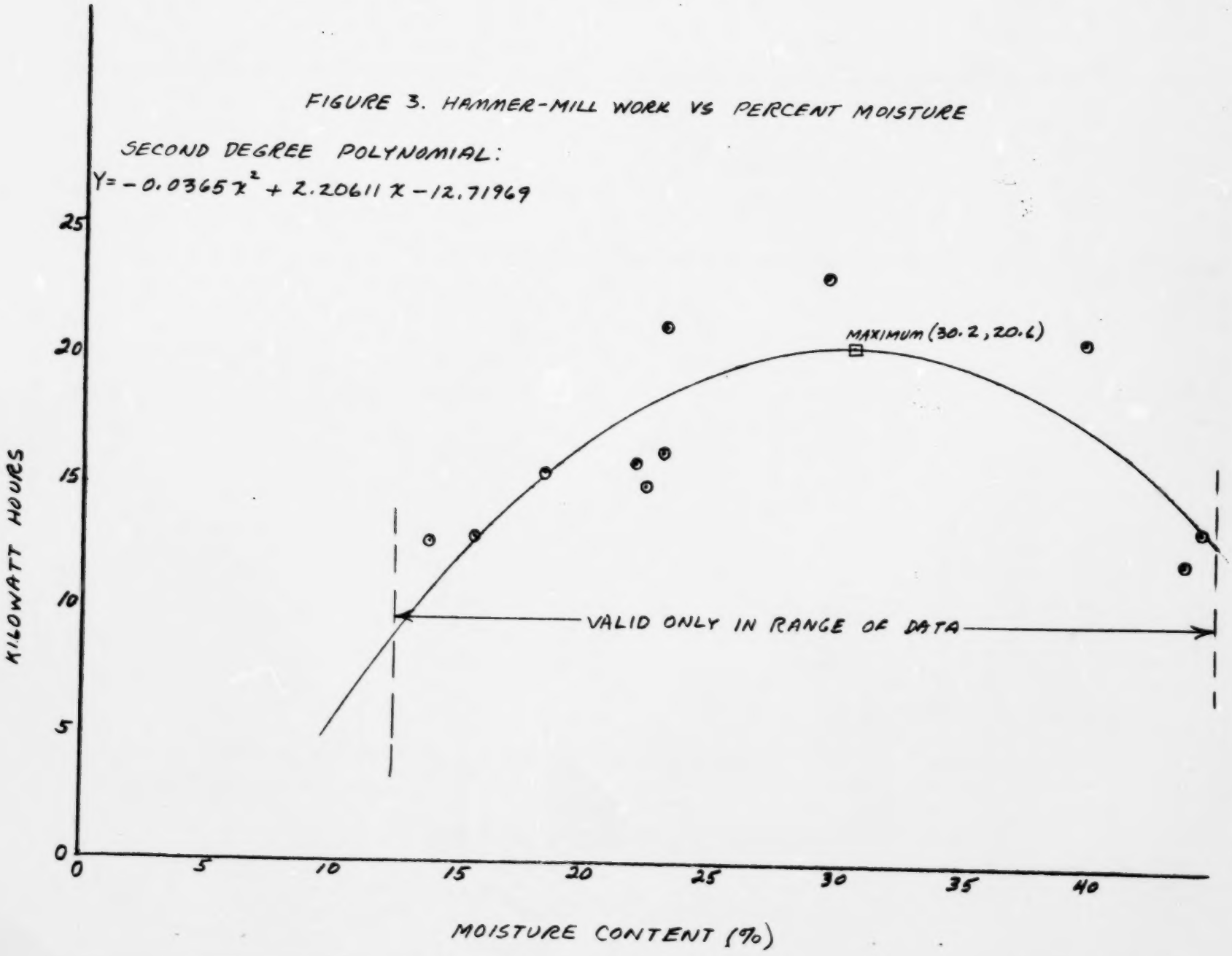


FIGURE 3. HAMMER-MILL WORK VS PERCENT MOISTURE

SECOND DEGREE POLYNOMIAL:

$Y = -0.0365X^2 + 2.20611X - 12.71969$



as moisture decreases. This reversal of the relationship of moisture content and net work will be due to the feeding problems causing over-grinding. However, additional work is required before this speculation can be substantiated.

Two mathematical models have been developed by the Statistical Source Section, Division of Technical Operations, Bureau of Solid Waste, describing the possible relationship between final moisture content and net work. The model which better fits the data is a third degree polynomial:

$$Y = -0.00292x^3+0.20783x^2-4.04849x+36.63050 \qquad \text{(Eq. 7)}$$

Where

Y = Net Work (kilowatt-hrs/ton)

x = Final Average Moisture Content (%)

The other proposed model is a second degree polynomial:

$$Y = 0.0365x^2+2.20611x-12.71969 \qquad \text{(Eq. 8)}$$

Where

Y = Net Work

x = Final Average Moisture Content (%)

More data is needed, however, before either of these models can be regarded as anything more than just a gross approximation of the relationship of refuse moisture content to net work.

CHAPTER VI

SUMMARY

A. Initial Conclusions From Research To Date

Although the experimental work using the hammermill is incomplete*, three conclusions have emerged from the relatively small amount of data. They are:

1. The size reduction and subsequent homogenizing of refuse after comminution in a hammermill is sufficient to prepare a representative sample of refuse--blending following comminution is not required.
2. A net decrease of moisture does occur while the refuse is being comminuted.
3. There is a correlation of the net work applied to the refuse and the final moisture content.

The level of homogeneity of refuse can be reasonably measured by the standard deviation of the moisture contents of many samples. Although moisture may be dispersed more easily than other materials such as aluminum, grease, or cellulose, at least this preliminary work indicates that very good mixing and homogenizing can occur after a refuse sample has been macerated in a hammermill with 1.5 inch grates.

The ability of the hammermill to drive away a portion of the moisture in refuse has not been a major discovery,

*A 5-year plan to study all types of size reduction processes at several locations has been proposed.

nevertheless, the accumulation of even the small amount of data thus far can be very useful. Some informal discussions with grinding "experts" indicated a belief that moisture weight reduction up to 20 percent is not uncommon when refuse is comminuted by a hammermill. This has not been substantiated by the experimental work. It appears that no more than a 6 percent moisture weight reduction occurs through comminution. Hammermills yielding a particle size less than 1.5 inches may drive away more than 6 percent moisture, since particle size is inversely proportional to work input(3).

The correlation between net work (the total work to comminute the refuse minus the work to run the hammermill with no load) and moisture content may be helpful in reducing power requirement by adjusting the moisture content of the refuse before grinding. However, until more data has been accumulated and a better understanding of the functional relationship (Eq. 7, Eq. 8) as well as the relative range of moisture content in which this relationship applies, only the fact that a relationship exists is valid. Any other definitive use of this data is premature.

B. Future Direction of Grinding Research

Future efforts will be directed toward:

1. A more exact interpretation of the functional relationship between net work and moisture content.

2. Compilation of operating costs.

3. Optimizing efficiency of grinding process.

Plans are being discussed to expand the research so that many size reduction processes, as well as conveying systems can be studied to determine the efficiency and operation costs of not only individual processes but also total systems. The study of total systems should eventually lead to recommendations for the most efficient, low cost method to presize solid wastes.

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